Deterioration of natural hydraulic lime mortars, I: Effects of chemically accelerated leaching on physical and mechanical properties of uncarbonated materials

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ABSTRACT

Masonry using lime binders is very common in all regions of the world. Models for the future climate in northern regions suggest more intense rainfall which will result in the materials used in mass masonry being saturated for longer periods and therefore at higher risk of binder leaching and consequent deterioration. In this first study of lime binder leaching, ammonium nitrate leachant was used to accelerate the deterioration of mortars containing natural hydraulic lime binders. Loss of binder reduced the alkalinity and strength of the mortar and increased its sorptivity. The leached depth followed diffusion-controlled kinetics with the rate constant increasing in line with the increasing free calcium hydroxide content of the binder. A predictive model was developed for uncarbonated mortars, such as those of all ages (historic or modern) found deep in mass masonry and those at early age in new construction or repairs.

Keywords: natural hydraulic lime, mortar, binder, dissolution, leaching

1 INTRODUCTION

Traditional stone masonry, consisting of units bedded in lime mortar, is common worldwide, with innumerable low rise dwellings, castles, palaces, bridges, viaducts and other infrastructural masonry (such as retaining walls) remaining in use. In Scotland alone there are an estimated 446,000 pre 1919 dwellings, totalling 20% of the building stock, and the vast majority of these are believed to be constructed of stone [1]. Urquhart [1] estimated that there are 24,000 traditional built stone and lime mortar facades in Glasgow, with a potential repair cost of about £0.5 billion. Anecdotal evidence from building professionals highlights situations where traditional mortars have been found to be deficient in binder [2-4], and in some cases, voids have been found in walls behind an apparently sound exterior. This has been associated with progressive collapse in traditional buildings [4]. McKibbins and Melbourne state that '*Contributory mechanisms for deterioration of masonry in all types of structures include moisture saturation and leaching of mortar…. Leaching results in physical loss of strength and adhesion. Mortar that has undergone severe leaching can become weak and friable, and is easily lost from joints by washing-out or compressive extrusion in areas of high stress, resulting in local stress concentrations and loosening of masonry units.*' [5]. Binder leaching is due to high moisture contents

in calcium-based materials and the increased rainfall associated with climate change [6,7] means that masonry will be wetter for longer. Soluble components within the mortar may dissolve and migrate through the material to be re-deposited within the pores, in construction voids (Figure 1), or as efflorescence on external faces of masonry.

The binder components vulnerable to dissolution are portlandite (calcium hydroxide, $Ca(OH_2)$) and calcite (calcium carbonate, $CaCO_3$) [8,9]. Less hydraulic limes may have a higher proportion of $Ca(OH)_2$ and are likely to be more reliant on carbonation for hardening as they contain a lower proportion of the hydraulic components. Whilst this does vary between different lime manufacturers, the hydraulicity of the original binder is expected to influence a mortar's long term performance. Less hydraulic lime binders should be more susceptible to dissolution, particularly in saturated, cold conditions because the solubility of both $Ca(OH)_2$ and $CaCO_3$ increases as water temperature decreases [10].

Figure 1: Stalactite (Speleothem) formation in a void within a masonry bridge pier confirms the migration of binder from the original lime mortar

The amount of $Ca(OH)_2$ within an existing historic mortar would be expected to be low, as it would have converted to calcite. However, Teutonico *et al* [11] suggest that it is not unknown for $Ca(OH)_2$ to remain uncarbonated over extremely long periods, even centuries. This is particularly pronounced in thick walls such as defensive structures and infrastructural masonry where CO_2 diffusion is slow, as confirmed by the uncarbonated 1700-year old lime found in Hadrian's Wall, UK [12].

The extent to which binder dissolution occurs and its impact on lime mortar has not been studied. However, it is anticipated that the rate of deterioration will be extremely slow, measured in decades rather than years and that an accelerated test method will be required. Despite these long time frames, it must be emphasised that many at-risk structures may already be old, and those considered historic may be centuries old, with a possible history of extant leaching. In contrast, leaching behaviour has been widely studied in Portland cement, where long-term damage by natural water has occurred [13-17]. Gaitero *et al* [18,19] and Berra *et al* [20] reported the beneficial effect of ultra-fine particles of pozzolanic silica on the leaching and consequent deterioration. Two principal techniques have been used to establish the long term leaching in cements and concretes: (i) chemical acceleration [17,20] and (ii) electrochemical acceleration [21]. The principle of chemical leaching is to promote reaction between calcium hydroxide (in the binder material) and ammonium nitrate in the leachant solution, forming gaseous ammonia and calcium nitrate, which is highly soluble in water (see equation 1).

$$Ca(OH)_2 + 2NH_4NO_3 = Ca(NO_3)_2 + NH_3\uparrow + NH_4OH + H_2O \quad (1)$$

This forms a NH_4^+/NH_3 buffer, whose pH level depends on the leachant concentration and on the liquid/solid ratio used in the test [20]. Nguyen *et a*l [17] used 8M ammonium nitrate on plain cement and achieved a 200-300 fold acceleration compared to deionised water, whereas Berra *et al* [20] used 6M leachant on blended cements. In this paper, the method has been refined to reflect the different composition of the lime binder. The loss of calcium from the hardened products changes the properties and performance of the mortar, allowing insights into the long term effect of leaching on the performance of mortars.

The research aimed to establish the rate of soluble binder leaching from various types of lime mortar commonly used in traditional mass masonry construction and new build applications, and determine the potential for binder loss from uncarbonated hydraulic limes and its effect on properties and performance. The objectives were to determine the rate of portlandite ($Ca(OH)_2$) leaching in a range of uncarbonated hydraulic lime mortars, using ammonium nitrate, and to assess the effect on strength and moisture handling characteristics. This would inform a method for predicting the service life of lime mortar. It must be emphasised that, although the whole programme investigated both uncarbonated and carbonated natural hydraulic lime mortars, this paper reports only the data for uncarbonated mortars: later papers will describe the carbonated mortars.

2 MATERIALS, SPECIMEN MANUFACTURE AND CURING

2.1 Materials and characterisation

Mortars at a constant binder to aggregate ratio of 1:3 (by volume) were used, selected for being commonly used for repairs to traditional stone masonry and for new construction, as well as being reasonably representative of historic mortars. Aggregate was sieved in accordance with BS EN 13139 [22] to determine the particle size distribution and the lime binder characterised by powder X-Ray diffraction (XRD), using a Thermo ARL X'TRA Diffractometer with a 2Theta range of 5º - 70º at a rate of 1º/min.

2.2 Aggregate

Well graded silicaceous sand (Cloddach concrete sand, Elgin, Scotland) was selected as it is representative of materials commonly used for the repair of traditional masonry structures in Scotland. The absence of calcareous minerals ensures that binder leaching is not confused with aggregate dissolution. Figure 2 shows the particle size distribution. The bulk density of the aggregate is 1500 kg/m^3.

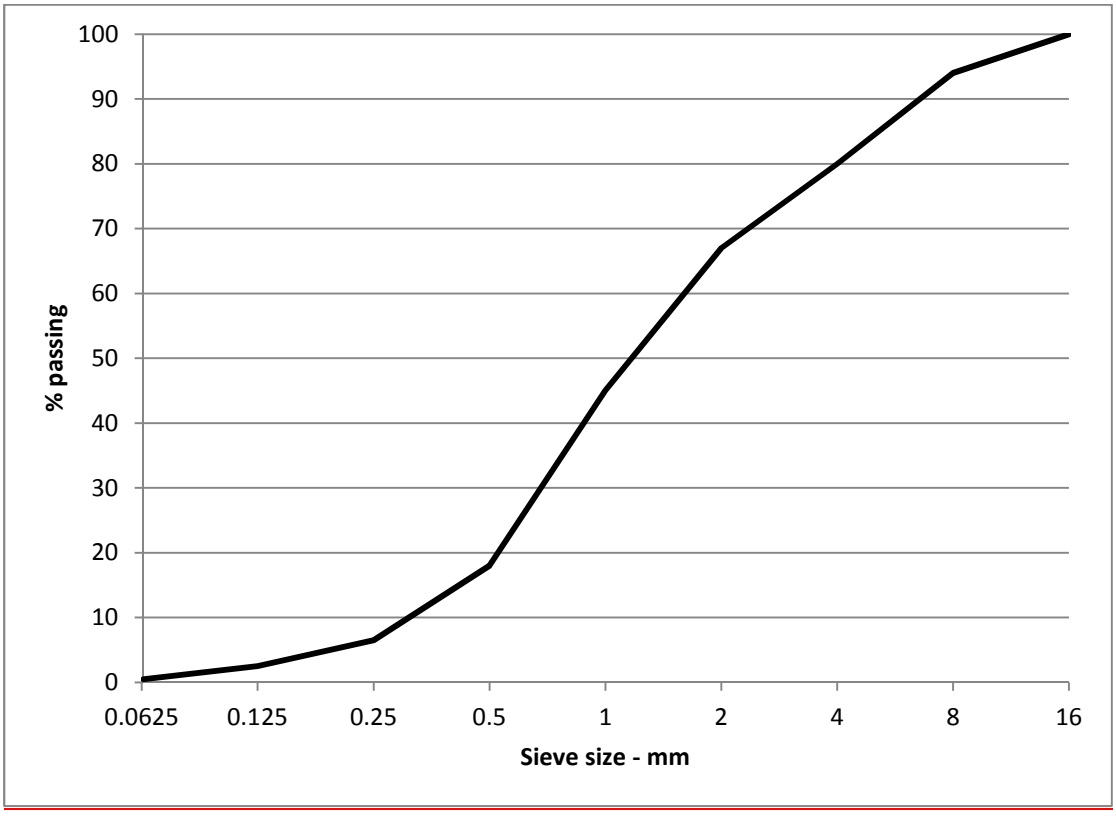
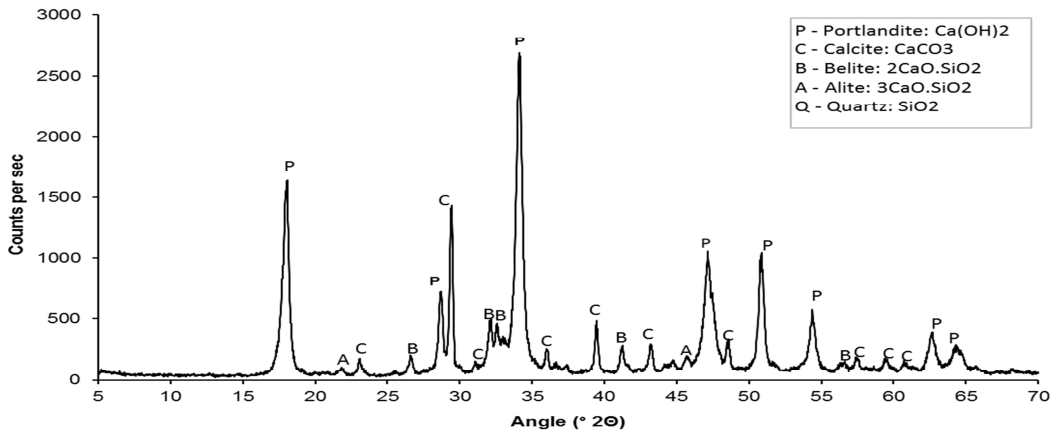


Figure 2: Particle size distribution for Cloddach concrete sand.

2.3 Binder

St Astier natural hydraulic lime (NHL) was used to reflect modern repair specification and application in the UK [23]. Three grades were used: NHL2 (feebly hydraulic), NHL3.5 (moderately hydraulic) and NHL5 (eminently hydraulic), complying with BS EN 459-1: 2010, and their mineral composition is shown in the X-Ray diffractograms in figure 3. Table 1 shows the anhydrous binder composition as provided by the manufacturer. The diffractograms agree with Table 1 in showing that the amount of portlandite decreases as the hydraulicity of the material increases. The quantity of $Ca(OH)_2$ influences the potential for leaching especially if it remains unconverted into $CaCO_3$ [10].

(a)



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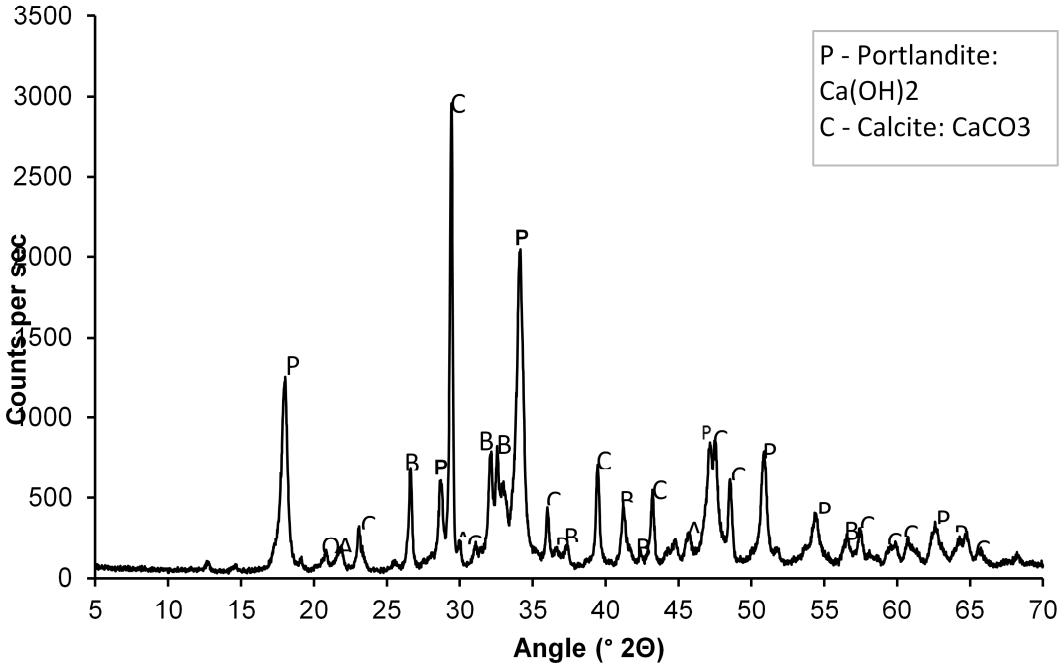

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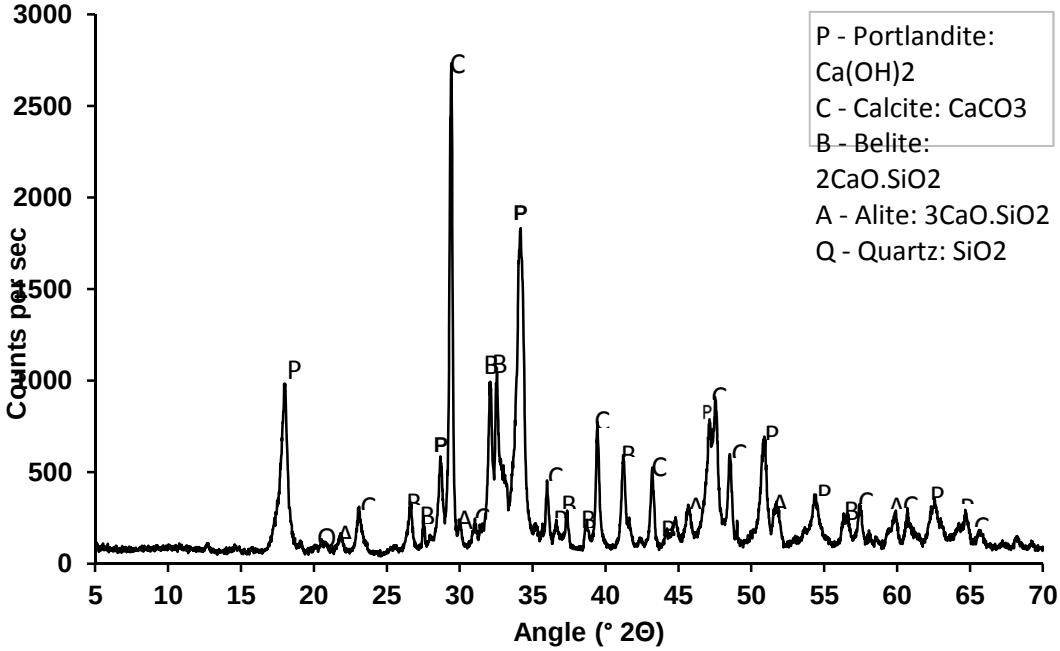

Figure 3: X Ray diffractograms for anhydrous Natural Hydraulic Lime (NHL) binders. (a) NHL2, (b) NHL3.5, (c) NHL5

Table 1 shows that the amounts of $Ca(OH)_2$ and C_2S (belite) and the relative bulk density all vary in line with the hydraulicity. The relative bulk density also reflects the particle size and shape.

Table 1: Chemical and physical properties of the NHL binders (source: manufacturer)

Binder	Bulk density kg/m^3	Mineralogical composition (%)							
		$CaCO_3$ unburnt	Insoluble	Free $Ca(OH)_2$	Compound				
					C_2S	C_3A	C_2AS	C_4AF	$CaSO_4$
NHL2	550	13	8	58	17	0.4	0.8	0.4	0.5
NHL3.5	620	25	9.6	25	35	0.5	1	0.5	0.8
NHL5	750	23	5.6	22	43	0.7	1.3	0.7	0.7

2.4 Mortar manufacture and batching

The mixing procedure for the manufacture of mortar test specimens was closely aligned to BS EN 459-2 [24] and BS EN 1015-2 [25] for the testing of lime mortars. The standards refer to the mixing procedure stipulated in BS EN 196-1 [26] for the testing of cements. Whereas BS EN 196-1 specifies a 1:3 ratio (1350g of aggregate to 450g of binder) with 225g of de-ionised water, BS EN 459-2 varies the

water content to ensure the mortar achieves a flow of 165±2mm for NHL2 and NHL 3.5 and a flow of 185mm ±2mm for NHL5 using a standard (BS EN 459-2) flow table apparatus. In this programme, the proportions were further modified to integrate the relative bulk density for the different binder types to ensure a constant 1:3 ratio by volume was maintained for all mortars (Table 2).

The mixing and casting of the mortars followed BS 459-2 (2010), except that 160x40x40mm steel gang moulds were replaced by polystyrene moulds in order to reduce the load on the environmental curing cabinet. The polystyrene gang moulds were not treated with releasing agent to avoid possible adverse effects on the mould material or the mortar. Table 2 indicates the quantities required for 8 litres (0.008 m^3) of mortar. 15 un-carbonated 160x40x40 mm prisms were produced for each NHL classification (2, 3.5 and 5) with three used as control samples to provide a baseline.

Table 2: Mortar mix data

Lime	Mass of material kg			Sand/lime by mass	Water/lime by mass	Flow value mm (±2mm)
	NHL	Sand	Water			
NHL 2	1.63	7.50	2.63	4.6	1.61	165
NHL3.5	1.89	7.50	2.73	4.0	1.44	165
NHL 5	2.05	7.50	2.75	3.7	1.34	185

2.5 Curing regime

The specimens were cured in a TAS series 3 environmental cabinet at 100% RH and 20°C for the first 7 days. The high humidity environment ensured that no carbonation could occur, whilst creating favourable conditions for the formation of the products of hydration from the hydraulic components. They were then demoulded, wrapped in damp hessian and placed in airtight containers over water to keep them damp. The containers were returned to the cabinet and the specimens cured for a total of 56 days following Pavia and Toomey's method [27].

3 EXPERIMENTAL PROCEDURE

3.1 Accelerated leaching

A preliminary experiment showed that Nguyen *et al*'s [17] immersion treatment using 8 M ammonium nitrate was too aggressive for NHL specimens. Therefore 1 M solution was used to accelerate the leaching of calcium (Ca^{2+}) ions. A Fluval 1 pump circulated the leachant solution around the tank (20 litres capacity, Figure 4), ensuring a uniform concentration of solution interacting with the specimens. The specimens were contained in individual wire cages for the ammonium nitrate experiments and placed on glass spacers for the deionised water experiments and then immersed for up to 169 days at 20±2°C. The volume of solution was maintained and its pH was continuously logged via a Tercel R21 data acquisition system (figure 4) to ensure that a pH of 8.5 or above was maintained. The control specimens were immersed in de-ionised water in parallel treatments for the initial 36 days.

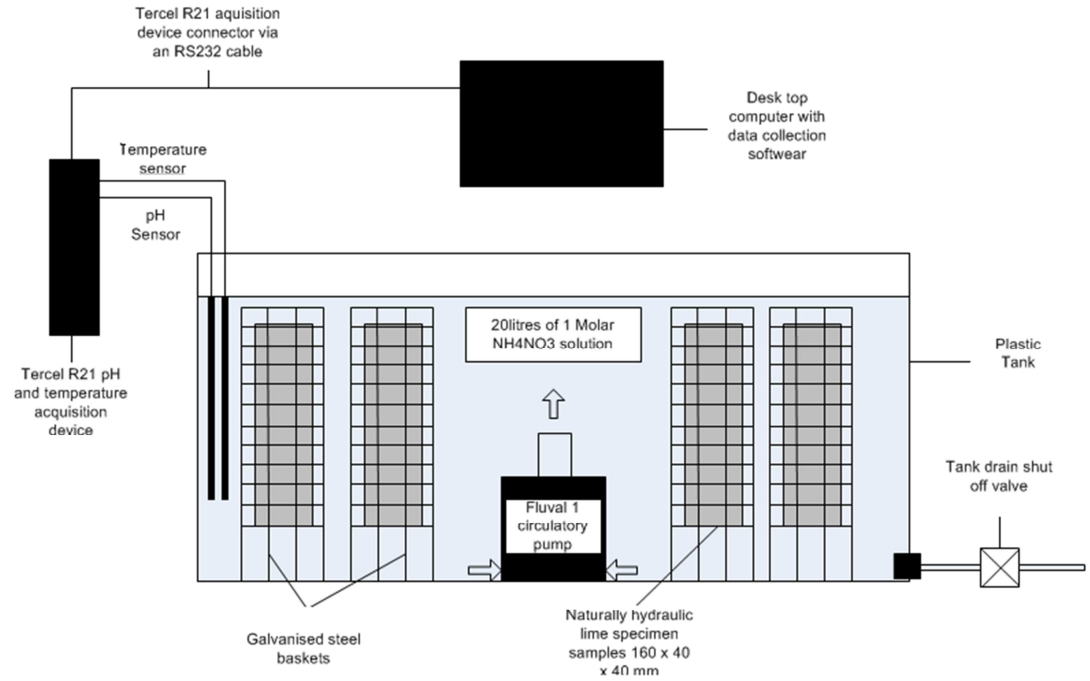

Figure 4: Ammonium nitrate extraction apparatus - modified from Nguyen [17]

3.2 Physical and chemical testing

Specimens were removed from solution after 1, 4, 9, 16, 25, 36, 100 and 169 days and tested as follows.

3.2.1 Flexural Strength

Flexural strength was tested according to BS EN 459-2 [24] using three point bending in a Lloyds universal MK5 instrument of 5kN maximum load capacity. Force was increased until failure occurred and the specimen broke in two. The two halves were preserved for other tests.

3.2.2 Calcium hydroxide leaching

The fractured surfaces were sprayed with phenolphthalein solution. This gave an indication of the leaching depth of the $Ca(OH)_2$. The leaching depth was measured from each face using digital callipers and reported as the average of four readings.

3.2.3 Sorptivity

The specimens were oven dried at 85ºC for 24 hours and then sorptivity determined according to Hall and Hoff's application of unsaturated flow theory [28]. Each specimen was allowed to cool and then five faces were coated with resin, leaving the 40 x 40 mm fracture surface uncoated. Each specimen was supported on a pair of glass rods located in the bottom of a container and the uncoated face immersed to a depth of 1mm in de-ionised water. Measurements of mass increase were taken at intervals over about one hour. The sorptivity determined from the slope of the straight line relationship between mass and $t^{1/2}$, is expressed in units of $mm/min^{1/2}$ [28], reflecting the volume (mm^3) absorbed through the contact face (mm^2). Sorptivity is a simply measured composite property of all porous materials, increasing in line with porosity and capillary attraction.

3.2.4 Compressive testing

Compressive strength was tested in accordance with BS EN 459-2 [24] using the remaining half of each prism. The fractured half was trimmed with a diamond saw to produce a 40mm cube which was then crushed in the Lloyds universal MK5 testing machine.

3.2.5 Point count evaluation of mortar composition

Point counting of thin sections, prepared and impregnated with resin to show porosity, was undertaken using an Olympus BH2 polarising microscope fitted with a Swift model F automatic point counter. 600 points were recorded using a 0.5mm stepping interval. In the example in Figure 5, the point at the cross-hair is counted as binder, aggregate or porosity depending on the colour.

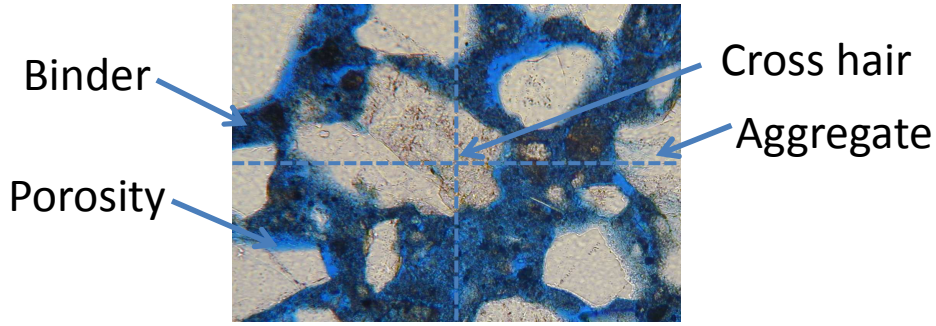

Figure 5: Point counting thin section image showing binder (dark grey), aggregate (light grey), porosity (blue) and cross-hair location.

4 RESULTS

Physical testing results for all uncarbonated specimens subjected to ammonium nitrate and water leaching will be discussed.

4.1 Compressive and flexural strength results

Table 3 shows that there is a clear difference between the specimens subjected to ammonium nitrate and to de-ionised water. As expected, those uncarbonated specimens containing a higher proportion of free calcium hydroxide (see Table 1) were more susceptible to a reduction in strength. Conversely, those materials with an increasing reliance on a hydraulic set (such as NHL5) demonstrated a smaller decline in strength over the entire test period. This reflects the relative stability of C-S-H [8] which forms the main component of the binding matrix in the limes of higher hydraulicity.

Table 3: Compressive, flexural strength and sorptivity results

		Compressive strength MPa				Flexural strength MPa				Sorptivity mm/t^{½}	
Binder	**Leachant**	**0 d**	**36 d**	**100 d**	**169 d**	**0 d**	**36 d**	**100 d**	**169 d**	**0 d**	**36 d**
NHL2	water	1.42	0.72			0.52	0.27			1.33	1.08
NHL3.5	water	2.2	2.72			0.91	1.02			0.52	0.15
NHL5	water	2.45	2.54			1.06	0.94			1.25	0.99
NHL2	NH_4NO_3	1.42	0.03	0.1	0.001	0.52	0.1	0.01	0	1.33	2.7
NHL3.5	NH_4NO_3	2.2	0.97	0.29	0.09	0.91	0.18	0.14	0.06	0.52	1.24
NHL5	NH_4NO_3	2.45	0.7	0.36	0.06	1.06	0.51	0.14	0.07	1.25	1.69

The NHL5 and NHL3.5 control specimens in deionised water exhibited a small increase in compressive strength and a stable flexural strength over the 0-36 day period. This is probably associated with the favourable curing environment for the development of the products of hydration, especially C-S-H. In contrast the NHL2 control specimens in deionised water decreased in both compressive and flexural strength by 50% over a 36 day period.

The effect of ammonium nitrate treatment on strength is dramatic, giving progressive reductions in compressive and flexural strength, leading to negligible strength remaining after 169 days (table 3). Strength loss was more rapid with NHL2 than with the other binders and this is consistent with the higher proportion of $Ca(OH)_2$ in that binder (table 1).

4.2 Sorptivity

Table 3 shows that the effect of ammonium nitrate treatment on sorptivity is the opposite of what happens in de-ionised water. In water sorptivity decreases up to 36 days by between 20% and 70%. This is undoubtedly due to the progressive development and densification of hydration products in the water saturated environment. The pores fill with C-S-H, formed over time, there is no loss of calcium hydroxide due to leaching and the measured sorptivity decreases. In contrast, ammonium nitrate treatment increases sorptivity by between 30% (NHL5) and 150% (NHL3.5) as calcium hydroxide is extracted, leaving more open porosity.

4.3 Calcium hydroxide leaching

Figure 6 (in colour in the online version of this paper) shows the results of spraying the fractured surface of leached specimens with phenolphthalein solution: the pink coloration denotes the high pH due to the presence of calcium hydroxide and the colourless areas are where calcium hydroxide has leached out.

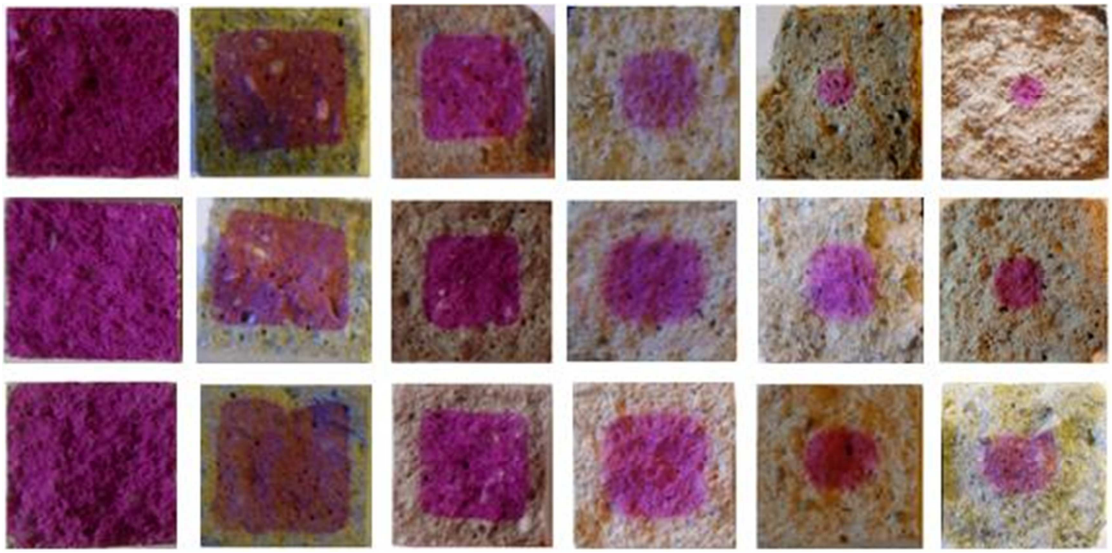

Figure 6: Phenolphthalein test results on uncarbonated samples subjected to NH_4NO_3 at 1-4-9-16-25-36 days (top NHL2, middle NHL3.5, bottom NHL5)

Calcium hydroxide leached faster from NHL2 specimens than from NHL3.5 and NHL5 specimens. The advancing dissolution front correlates with the physical testing results over the same 36 day period.

4.4 Point counting evaluation

Point counting identifies the presence or absence of binder at each point but does not take into account any changes in binder density. Nevertheless figures 7-9 reflect the trends associated with the strength, sorptivity and $Ca(OH)_2$ leaching. Point counting shows a reduction in the binder concentration and an associated increase in porosity. The point count at 36 days for the NHL5 mortars (figure 9) correlates with the phenolphthalein test results, showing a higher binder concentration and lower porosity at the centre than at the outer surfaces. In contrast, NHL2 mortar at 36 days (figure 7) shows a higher binder concentration and lower porosity at the outer surface. This does not reflect the phenolphthalein results and may be due to the high mobility of calcium hydroxide within the specimen. The NHL3.5 mortar exhibits a negligible difference between the outer and centre at 36 days. The precision of point counting data depends on the number of points counted. According to a nomogram shown by St John et al [29], 600 points showing a component to be present at 25% by volume corresponds to a relative error of ±4% in the values shown in figures 7-9.

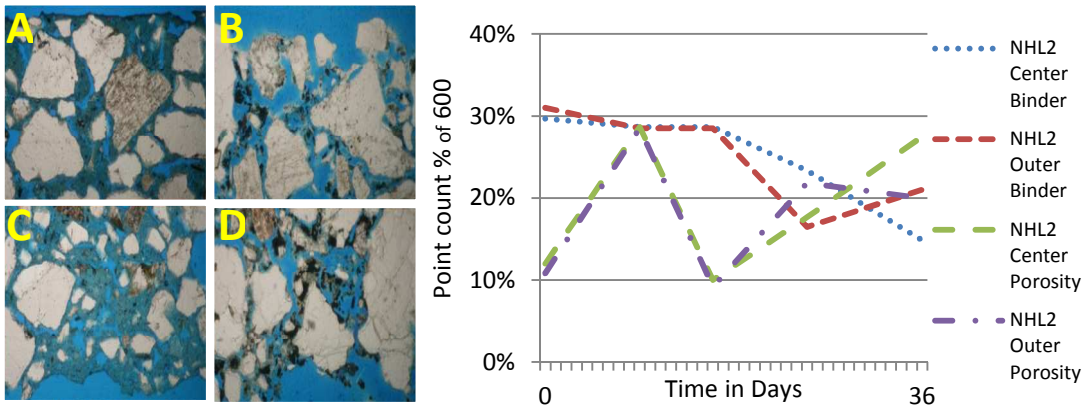

Figure 7: Uncarbonated NHL2: (Left) images: (A) Initial outer, (B) 36 days outer, (C) Initial inner, (D) 36 days inner. (Right) Point counts of binder and porosity

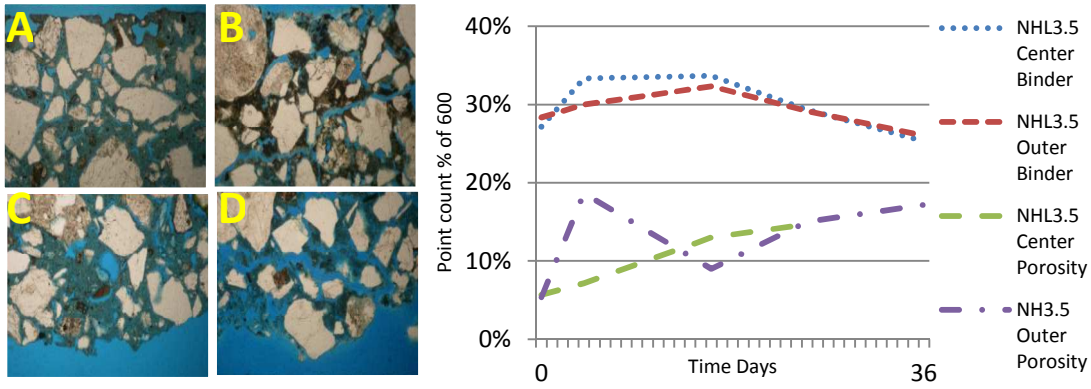

Figure 8: Uncarbonated NHL3.5: (Left) images: (A) Initial outer, (B) 36 days outer, (C) Initial inner, (D) 36 days inner. (Right) Point counts of binder and porosity

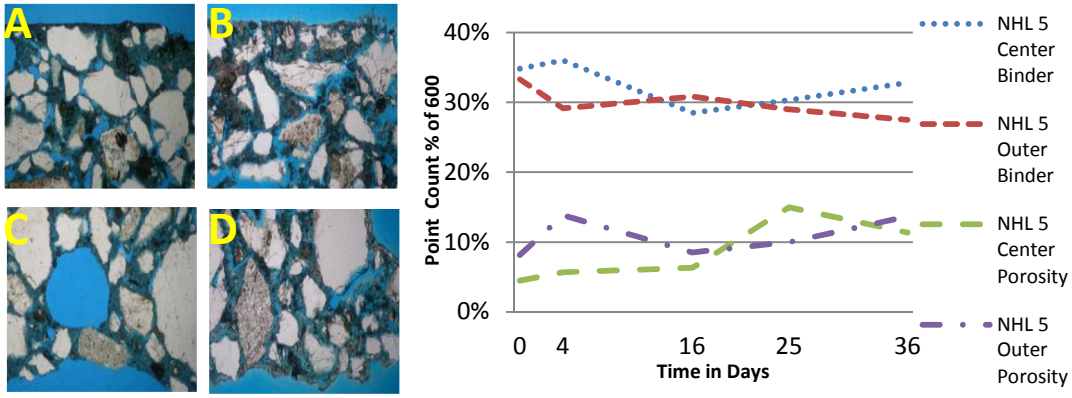

Figure 9: Uncarbonated NHL5: (Left) images: (A) Initial outer, (B) 36 days outer, (C) Initial inner, (D) 36 days inner. (Right) Point counts of binder and porosity

5 DISCUSSION

All the results presented here relate to uncarbonated natural hydraulic lime mortars: they can be taken as relevant to mortar in the core of existing thick masonry construction but also to new build work at early ages before significant carbonation has taken place. They may not be relevant for air limes because hardened NHLs contain some hydrated products. However, equation 1 also applies to an uncarbonated air lime but can be rewritten for a carbonated air lime as:

$$CaCO_3 + 2NH_4NO_3 = Ca(NO_3)_2 + (NH_4)_2CO_3 \quad (2)$$

Since both calcium nitrate and ammonium carbonate are highly soluble leaching would be expected to occur in broadly the same way as observed in this study, although the rates would be different. Phenolphthalein spraying, sorptivity and strength have established that dissolution of calcium ions from $Ca(OH)_2$ in the matrix is accelerated by ammonium nitrate. The resistance to leaching is influenced by the relative proportion of C-S-H within the matrix. As expected, the most hydraulic lime (NHL5), with its highest C_2S content, shows the highest resistance to leaching. This has implications for the performance of uncarbonated lime mortars subject to long term saturated conditions: higher hydraulicity binders perform better. In contrast, leaching is barely discernible with de-ionised water because of the favourable curing conditions for the development of hydraulic phases. Increasing the depth of the dissolution front can be directly related to increasing sorptivity, and decreasing compressive and flexural strengths. The higher leaching rate in NHL2 specimens can be attributed to the relatively high concentration of $Ca(OH)_2$ in the material. Figures 10 and 11 show the relationships between leaching depth, sorptivity and strength. There is a clear increase in sorptivity and leaching depth over time, and a less clear-cut but still significant decrease in strength.

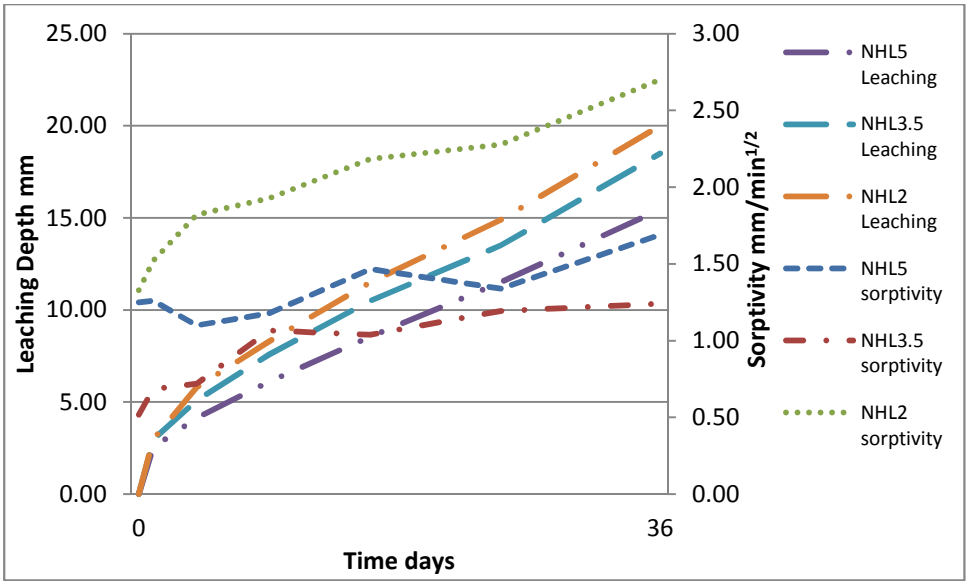

Figure 10: Binder leaching depth and sorptivity for NHL2, 3.5, and 5 uncarbonated mortar.

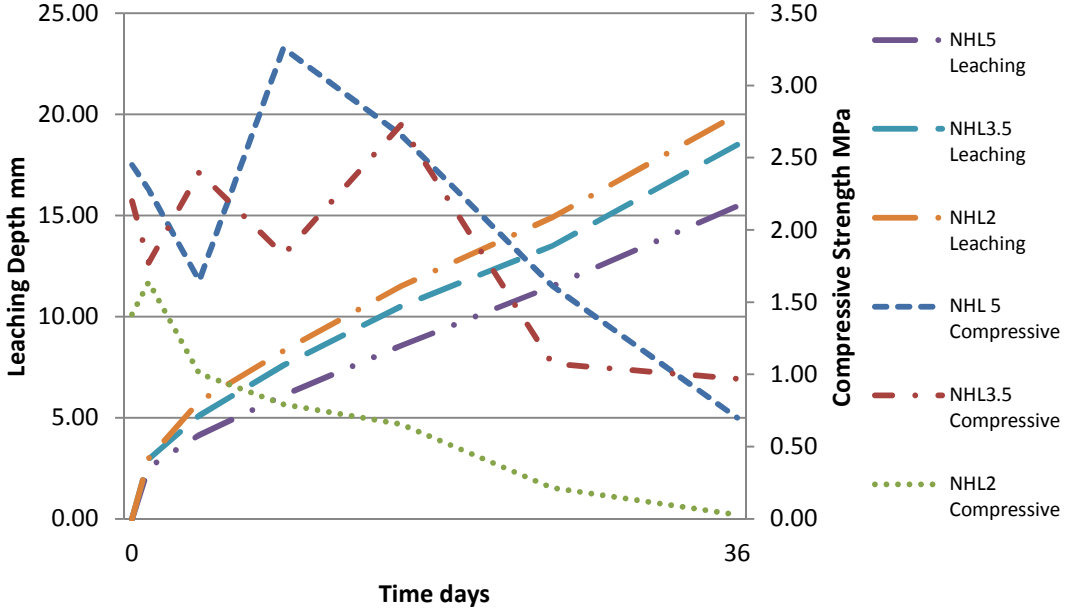

Figure 11: Binder leaching depth and compressive strength for NHL2, 3.5, and 5 uncarbonated mortar.

Considering the kinetics of $Ca(OH)_2$ leaching, it is to be expected that the leaching process is diffusion controlled and in this case leached depth h is proportional to the square root of time according to

$$h = k\, t^{½} \qquad (1)$$

where k is a constant that depends on the composition of the material and the chemical environment. Additionally, Berra *et al* [20] propose that the reciprocal of k can be taken as an index of resistance to

leaching and is therefore a material parameter. Figure 12 shows that the value of *k* correlates with the observed results: NHL2 (feebly hydraulic) lime has the highest value of 3.1 mm/day^{½} (lowest resistance) and NHL5 (eminently hydraulic) the lowest value of 2.3 mm/day^{½} (highest resistance). In principle, these trends could be extrapolated to develop predictions of leaching depth in larger sections of uncarbonated masonry.

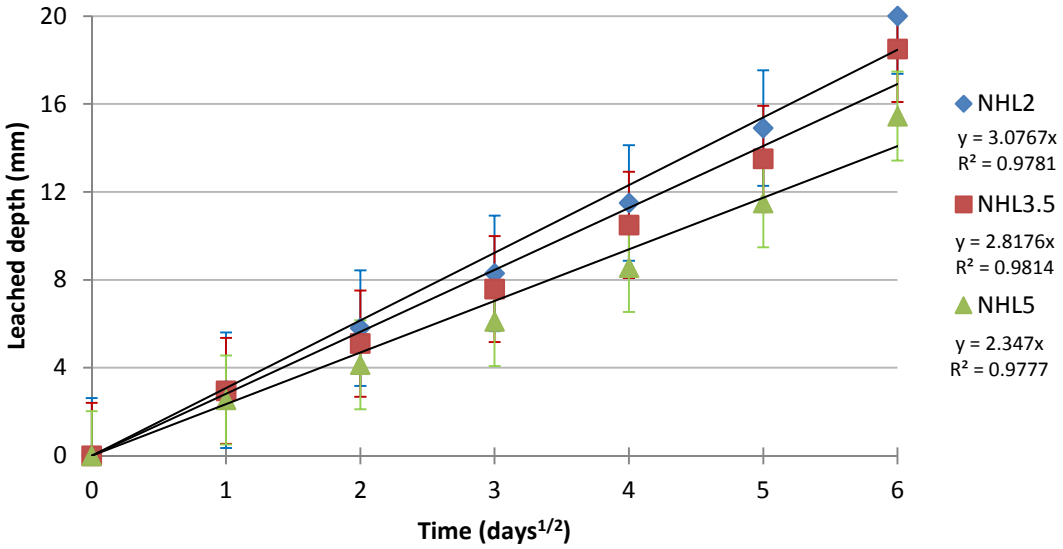

Figure 12: Relationship between leaching depth and time for uncarbonated NHL2, 3.5 and 5 specimens

For example, the leached depth at 365 days is estimated to be 59, 53 and 46mm for NHL2, NHL3.5 and NHL5 respectively. Alternatively the time taken to leach to a depth of 300mm is 25.7 years, 31.5 years and 42.8 years respectively. While the confidence interval on these values is about ±12.5% these data at least illustrate the principle. All that is needed to predict binder loss in a practical situation is the acceleration factor due to the ammonium nitrate leaching solution.

In cement, Nguyen *et al* [17] reported an acceleration factor of 200-300 for the 8M ammonium nitrate treatment compared to de-ionised water. Our work used 1M leachant which would be expected to have a much lower factor, but only NHL2 showed measurable leaching in de-ionised water, to a depth of 1mm in 36 days. This suggests an acceleration factor of 20. Applying this factor to the values obtained from figure 12 gives values of *k* (equation 1) of between 0.12 and 0.15 mm/day^{½} for the NHL mortars tested. This suggests leaching depths in the field of between 24 and 30 mm in 100 years. Whilst no

direct field data exist, the validity of these values can be considered in the context of the stalactite growth visible in figure 1.

Assuming that a stalactite is a solid cone of calcium carbonate and has a base diameter of 10mm and a length of 1 m, its volume is 0.026×10^6 mm^3. (It is accepted that not all stalactites are solid but no experimental characterisation of those shown in Figure 1 is available. The assumption of solidity sets an upper boundary to the discussion that follows.) The mass of Ca^{2+} in this volume of calcium carbonate (density 2700 kg/m^3) is 0.028 kg. Figure 1 suggests that there is one stalactite per 200 mm length of mortar joint and the joint is 20 mm wide, i.e. 0.028 kg of Ca^{2+} has leached from 4000 mm^2 of exposed surface area of mortar. The question is the depth *H* of lime mortar of this surface area that would yield this quantity of Ca^{2+}. Taking the mortar density as 1500 kg/m^3 and assuming that its volumetric mix proportions are 1:3 lime:sand and that the lime consists of 70% CaO by mass, it can be shown that the mass of Ca^{2+} in $4000H$ mm^3 of mortar is $750H \times 10^{-6}$ kg. Equating this to the mass of Ca^{2+} in the stalactite yields a value of 37.5 mm for *H*, i.e. the stalactite considered could have formed by leaching of Ca^{2+} from 37.5 mm depth of mortar. The values of *k* (equation 1) quoted above suggest that leaching to this depth would take 171-267 years. If the stalactite modelled is hollow the time taken to leach sufficient material to produce it will be shorter than this. History records that the structure in figure 1 was started in 1830 and completed in 1864, a maximum of 175 years at the time of the image. Considering the uncertainties in the extrapolation process, this agreement is encouraging and suggests that acquisition of further field data including analysis of stalactites and any accompanying stalagmites would enable refinement and confirmation of the model.

Whereas the results presented in this paper allow a first step towards a prediction model, further investigations are needed in order to establish other effects such as water composition (e.g. Hardness and pH) and whether it is flowing or stationary. Additionally, comparative experiments on 'site-leached' and 'accelerated-leached' mortars, using for example SEM, could add further support to the conclusions.

6 CONCLUSIONS

1. Molar ammonium nitrate solution has been shown to be a satisfactory leachant for accelerated deterioration studies on natural hydraulic lime binders in masonry mortar. It is able to extract calcium from laboratory specimens in a reasonable time for comparative studies of binder loss in uncarbonated mortar.

2. Leaching of calcium from the binder reduces the alkalinity and strength and increases the sorptivity of NHL mortar, with the kinetics following a diffusion-type law, where leached depth is proportional to the square root of leaching time. The rate constant increases from NHL5 to NHL3.5 to NHL2, i.e. as the lime binder becomes less hydraulic. This is consistent with NHL5 mortars having the highest leaching resistance.

3. Preliminary evidence suggests that 1M ammonium nitrate accelerates leaching 20-fold compared to pure water and this has been shown to be consistent with evidence from the field, although more field data is needed before widely applicable predictions can be made.

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